

## Stable Isotope Ratios as Probes of Photochemistry in the Solar Nebula

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There is increasing appreciation for the link between photochemistry in protoplanetary environments and the chemical and isotopic compositions of solar system materials, including organics. Where column densities were relatively low in the protoplanetary disk that was the solar nebula, high fluxes of ultraviolet and x-ray photons will have modified the chemical and isotopic compositions of inorganic and organic materials. Once these materials were incorporated into planetesimals, further processing occurred by reactions with ice melts. Convolution of these processes produced complicated chemical and isotopic signals that are just beginning to be unraveled. It is possible that photochemistry near the surface of the Sun's accretion disk was one of the most important factors that controlled the synthesis of organic materials evidenced today in carbonaceous chondrite meteorites. The geometry of disks (e.g., flaring) and the vigor of turbulence within the disk control the degree of linkage between the chemistry of solids in the planet-forming regions and the photochemical zones near disk surfaces.

The isotopes of oxygen in the solar system may provide evidence for photochemistry in the solar nebula disk. Self shielding of CO to produce oxygen depleted in  $^{16}\text{O}$  is sure to have occurred at some level in the diffuse regions of the nebula. Calculations show that attenuation of a stellar flux of UV photons illuminating the disk surface is small enough that many Earth masses of oxygen with large depletions in  $^{16}\text{O}$  relative to the starting materials would have been produced above and below the midplane of the early solar nebula over time scales  $> 10^3$  years. The most likely sink for the  $^{17}\text{O}$  and  $^{18}\text{O}$ -rich oxygen liberated by photolysis of CO ( $\text{Q}^*$ ) would have been adsorption onto solid dust grains followed by surface reactions to produce water. Settling of these dust grains and radial transport toward the accreting star brings this source of  $^{16}\text{O}$ -depleted oxygen into the nascent inner solar system where it can react with gases, minerals, and liquids that form planet precursors.

Many observations are consistent with photodissociation of CO in the diffuse regions of the solar nebula as an explanation for the slope-1 line in oxygen isotope space. It accounts for the fact that  $\text{H}_2\text{O}$  was almost certainly depleted in  $^{16}\text{O}$  (enriched in  $\text{H}_2\text{Q}^*$ ) relative to silicates and other metal oxides in the solar system (in this way the model is consistent with that proposed for molecular clouds). Reactions between  $\text{H}_2\text{Q}^*$  and CO in the inner solar nebula (at higher  $T$ ) would not affect the slope-1 relationship in three isotope space because the mass-dependent fractionation between  $\text{H}_2\text{O}$  and CO is small at all relevant temperatures. Production in the outer solar nebula also provides a natural explanation for the correlation between  $^{16}\text{O}$  and the refractory nature of solids; refractory minerals would retain their original  $^{16}\text{O}$ -rich compositions because they would have had limited opportunity for reaction with  $\text{H}_2\text{Q}^*$  during transit through the nebula. The fact that some refractory materials retain isotope anomalies that cannot be explained by proximity the nascent star attests to their unreactive nature during transit.

Photodissociation of CO high above the midplane at large  $R$  is an attractive explanation for the oxygen isotope slope-1 line. Distinguishing between self-shielding by CO in the diffuse molecular layers of the nebula and similar processes in the parent molecular cloud will require detailed assessments of the collateral isotopic effects associated with photochemistry in both regions.

